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**PATENT APPLICATION**

**DISTRIBUTED LOAD TRANSMISSION LINE MATCHING NETWORK**

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## DISTRIBUTED LOAD TRANSMISSION LINE MATCHING NETWORK

### BACKGROUND OF THE INVENTION

5           The present invention relates to a matching circuit that reduces power reflected from a plasma formed in a substrate processing chamber. The invention is useful in a variety of technologies but is particularly useful in the manufacture of integrated circuits.

10           Plasma processing is a common step in the manufacture of integrated circuits. Common plasma processing steps include plasma enhanced chemical vapor deposition, reactive ion etching, and sputter etching among others. In such plasma processing steps, precise control of the plasma can be important in order to meet the manufacturing requirements of today's integrated circuits.

15           Typically a plasma is generated by applying RF energy to a coil or plates of a capacitor (inductive vs. capacitive coupling). To efficiently couple RF energy into a substrate processing chamber matching networks have been used to minimize the energy reflected from a plasma back into the RF generator. The source impedance of an RF generator is constant, typically 50 ohms resistive and zero ohms reactive, while the load of the plasma is transient and variable. The matching network  
20 matches the impedance of the load to an RF source from the perspective of the source. Thus, matching networks maximize RF power supplied to the load by minimizing the RF energy reflected from the load.

25           A variety of matching networks have been developed and successfully used in substrate processing. Fig. 1 is a block diagram of a previously known ac energy delivery system 10. As shown in Fig. 1, energy delivery system 10 includes a matching network 20a coupled by transmission lines 30a-b between an ac power source 40 and a plasma load 50. The matching network is comprised of tuning elements 60a-b that include capacitors, or inductors, or both. The matching network of Fig. 1, having  
30 tuning element 60a in parallel with the ac power source and the plasma load and having tuning element 60b in series with the source and load is commonly referred to as an "L network."

          Figs. 2 and 3 are block diagrams of energy delivery systems 12 and 14 having other previously known matching networks 20b and 20c, respectively.

Matching network 20b of Fig. 2 is commonly referred to as a "T network." T networks typically have one tuning element 60a coupled in parallel with the ac power source 40 and plasma load 50 and have two tuning elements 60c and 60b in series with the ac power source and plasma load. Matching network 20c shown in Fig. 3 is commonly referred to as a " $\pi$  network." Typically  $\pi$  networks have two tuning elements 60a and 60d coupled in parallel with ac power source 40 and plasma load 50 while having three tuning elements 60b, 60c and 60e in series with the ac power source and plasma load.

The tuning range of a matching network is a measure of the range of impedance for which disparate load and source impedances can be effectively matched. For example, if the impedance of an ac power source is 50 ohms resistive and a load is 100 ohms resistive and 10 ohms reactive but varies by  $\pm 10$  ohms resistive and  $\pm 5$  ohms reactive, a matching network tuning range would be sufficiently broad to effectively match these impedances. The tuning range of a matching network is typically related to the number of tuning elements in the network. Thus, a  $\pi$  network typically has a broader tuning range than a T network and a T network typically has a broader tuning range than an L network. However, matching networks having a relatively large number of tuning elements have a relatively higher resistance than matching networks having fewer tuning elements. Thus, total ac energy transfer is typically lower in matching networks with a relatively large number of tuning elements.

Matching networks such as networks 20a-20c shown in Figs. 1-3 can include tuning elements that are fixed or variable. Variable tuning elements, which include variable capacitors, and/or variable inductors, provide a matching network with continuously adjustable impedance matching. Such continuous adjustability provides the benefit of continuously matching the impedance of an ac power source to a load that has transient and variable impedance. Thus, a controllable amount of energy transferred to a load. For example, if the load is a plasma having a transient and variable impedance, by supplying a controllable amount of energy to the plasma through impedance matching, the plasma can be maintained in a relatively stable state.

The cost of variable components is considerably higher than the cost of fixed components. Thus, matching networks that use fixed components are generally less expensive than matching networks that use variable components. Such fixed-element matching networks have limited impedance matching capability, however. Thus, optimal impedance matching is not always achieved with fixed components. To

partially overcome the lack of continuous adjustability using fixed components, some previously known matching networks include parallel banks of fixed component tuning elements to provide step wise adjustability. Fig. 4 is a block diagram of an energy delivery system 16 having a step wise adjustable matching network 20d. Step wise adjustability is achieved by switching banks of tuning elements 70a...n into or out of connection with ac power source 40. Each bank of tuning elements 70a...n can be any of the previous described configurations of tuning elements, "L network", "T network" or " $\pi$  network." While step wise adjustable matching networks provide improved impedance matching capabilities, such matching networks have regions for which optimal energy coupling to a plasma load cannot occur.

Accordingly, it is desirable to develop matching networks that have low cost fixed components while providing improved impedance matching over a broad range of RF wavelengths and high energy transfer.

#### SUMMARY OF THE INVENTION

The previously identified needs as well as other needs are solved by embodiments of the present invention, which provide an apparatus and method for matching the impedance of a load to an ac power source. The apparatus includes a matching network coupled between an ac power source and a load. The matching network provides an increased tuning range for matching the impedance of the ac power source to the load. More specifically, an ac power source having a fixed source impedance can be matched to a load having a transient and variable impedance while the matching network effectively minimizes ac energy reflected from the load by improving power delivered to the load.

Embodiments of the present invention provide the above recited features through the use of two transmission lines that inductively couple an ac power source to a load. To both maximize ac energy transferred to the load and to minimize reflected energy, a fixed length of two transmission lines are placed in close proximity for at least one wavelength of the ac energy produced by the ac power source.

The apparatus and methods of use of the present invention are important to the manufacture of integrated circuit devices in which an RF source having a fixed impedance is coupled to a plasma load having a transient and variable impedance. The present invention is applicable to an ac energy delivery system in which ac energy

delivered to a load needs to be maximized through the minimization of reflected energy. In integrated circuit manufacture plasma processes, both deposition and removal processes are less reliable when reflected energy is not minimized. Embodiments of the invention can be used to minimize reflected energy for plasma processes through the inductive coupling of an RF source to a plasma load by inductively coupling two transmission lines for at least one wavelength of RF energy, thus stabilizing plasmas used in the manufacture of integrated circuits.

These and other embodiments of the present invention, as well as its advantages and feature are described in more detail in conjunction with the text below and attached figures.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a prior art ac energy delivery system that includes an L-network, matching network;

Fig. 2 is a block diagram of a prior art ac energy delivery system that includes a T-network, matching network;

Fig. 3 is a block diagram of a prior art ac energy delivery system that includes  $\pi$ -network, matching network;

Fig. 4 is a block diagram of a prior art ac energy delivery system that includes a matching network having banks of parallel tuning elements coupled to connecting switches;

Fig. 5 is a block diagram of an ac energy delivery system that includes one embodiment of a matching network of the present invention;

Fig. 6 is a block diagram of an ac energy delivery system that includes another embodiment of a matching network of the present invention;

Figs. 7A-C are diagrams of insulators within a ground shields according to embodiments of the present invention; and

Fig. 8 is a block diagram of an ac energy delivery system that includes another embodiment of a matching network of the present invention.

#### DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 5 is a block diagram of an ac energy delivery system 100 according to one embodiment of the present invention. AC energy delivery system 100 includes a

matching network 110a that inductively couples an ac power source 120 to a load 130, such as a plasma processing chamber. The ac power source is coupled to a transmission line 140a to deliver ac energy to the transmission line. Transmission line 140a is inductively coupled to a second transmission line 140b. Transmission line 140b is further coupled to the load 130. Transmission line 140b inductively receives ac energy from transmission line 140a and further delivers the ac energy to the load 130. The mutual inductance of two transmission lines is proportional to the length of both of the transmission lines and inversely proportional to the distance between them. To effectively control the mutual inductance of the two transmission lines 140a-b they are placed within close proximity of each other and are enclosed within a single ground shield 150 for a limited portion of their overall length. Typical spacing between the transmission is in the range of about 5 cm to 0.5 cm. The portion of the two transmission lines not inside ground shield 150 may be enclosed in separate ground shields that limit the mutual inductance of the transmission lines. The length that the two transmission lines are inductively coupled is herein after referred to as an "inductive length." Fig. 5 shows the two transmission lines to be parallel within the inductive length. An insulator 160 holds the transmission lines 140a-b in a fixed parallel position. Figs. 7A and 7B show varying views of insulator 160 inside ground shield 150. Fig. 7A shows insulator 160 (having a dashed outline) inside ground shield 150 (having a solid outline) from an end perspective; central circles 165 represent openings into which the first and second transmission lines are placed. Fig. 7B shows a side view of insulator 160 inside of ground shield 150. Central openings 165 are parallel to fix the first and second transmission lines in a parallel position as previously described.

Energy transfer from the ac power source and first transmission line to the second transmission line and load is improved if the inductive length is at least one wavelength of the ac energy. Thus, in order to ensure energy reflected from the load back to the ac power source is effectively minimized, the inductive length should be at least one wavelength of the ac energy. AC energy traveling in transmission line 140a not inductively coupled to transmission line 140b is prevented from reflecting from ground by a trimming element 170. Trimming element 170 is typically a register used to match the transmission line impedance to ground.

One application of the matching circuit of the present invention is to couple an RF source to a gaseous species within a substrate processing chamber to

generate a plasma. For a substrate processing system typical ac energy delivered by an ac power source ranges from radio frequencies to microwave frequencies, approximately 100 kHz to 2.45 GHz. Typical RF energy used for plasma generation is in the range of about 350 kHz to 400 MHz. Thus, the inductive length of the

5 transmission lines of the present invention is in the range of 3000 meters to about 0.12 meters and more typically between about 857 meters to about 0.75 meters. These inductive coupling lengths are quite long with respect to other equipment used in substrate processing. To make the embodiments of the present invention practical for use, the transmission lines and ground shield can be bent into various shapes to reduce  
10 their overall dimensions. For example, the transmission lines and ground shield can be bent into spirals, coils, or serpentine as well as other shapes. Such shapes can be less than a meter across in any direction, thus, making the dimensions of the transmission lines practical for use. In embodiments of the present invention discussed below, these dimensional issues are further addressed.

15 Fig. 6 is a block diagram of an AC energy deliver system 100 according to a second embodiment of the present invention. As similarly shown in Fig. 5 and similar to previously described embodiments, AC energy system 100 includes a matching network 110b that inductively couples an AC power source 120 to a load 130, such as a plasma processing chamber. The ac power source is coupled to transmission  
20 line 140a to deliver ac energy to the transmission line. Transmission line 140a is inductively coupled to a second transmission line 140b. Transmission line 140b is further coupled to the load 130. Transmission line 140b inductively receives ac energy from transmission line 140a and further delivers the ac energy to the load 130. First and second transmissions lines 140a and 140b are inductively coupled over an  
25 inductive length of at least one wavelength of incident ac energy. The spacing between the first and second transmission lines as shown in Fig. 6 varies along the length of the lines. Similarly described, the angle between the two transmission lines is non-zero. The transmission lines are held fixed within insulator 160. Fig. 7C shows a side view of insulator 160 inside ground shield 150. Openings 165 in insulator 160 are positioned  
30 such that the transmission lines are fixed as previously described.

The variable spacing between the transmission lines as shown in Fig. 6 minimizes ac energy reflected from the load to the ac power source if the inductive length is at least one wavelength of the ac energy generated by the source. AC energy

traveling in transmission line 140a not inductively coupled to transmission line 140b is prevented from reflecting from ground by a trimming element 170.

Fig. 8 is a block diagram of AC energy delivery system 100 incorporating a third embodiment of a matching network 110c of the present invention.

5 The matching network inductively couples an ac power source 120 to a load 130, such as a plasma processing chamber. The ac power source is coupled to a transmission line 140a to deliver ac energy to the transmission line. Transmission line 140a is inductively coupled to a second transmission line 140b. Transmission line 140b is further coupled to the load 130. Transmission line 140b inductively receives ac energy  
10 from transmission line 140a and further delivers the ac energy to the load 130. In the third embodiment transmission lines 140a-b are both coiled. The coils of transmission line 140a have a constant radius of curvature, while the coils of transmission line 140b have a radius of curvature that increases from one end of the coils to the other end. The coils of transmission line 140a surround the coils of transmission line 140b. Similar to  
15 the previously discussed embodiments, to minimize reflected ac energy, both transmission lines are inductively coupled for at least one wavelength of ac energy generated by the ac power source. Similarly described, the transmission lines have an inductive length of at least one wavelength of ac energy generated by the ac power source. This embodiment is relatively physically small as compared to the previously  
20 described embodiments and further spiraling, coiling, or serpentineing of the ground shield and enclosed transmission lines is generally not necessary.

A number of different embodiments of matching networks have been described above, as well as methods for use. As will be appreciated by one of ordinary skill in the art, the embodiments described above are exemplary only. The present  
25 invention has application for other ac power delivery systems when power transfer needs to be maximized through minimal reflection for an ac power source coupled to a load, when both source and load have either real or complex impedances that are mismatched.

Although the present invention has been described and illustrated in  
30 detail, it is to be clearly understood that the above descriptions and illustrations are by way of example only and are not to be taken as limiting the invention, the spirit and scope of the present invention being limited only by the terms of the appended claims.